1 MV LONG PULSE GENERATOR WITH LOW RIPPLE AND LOW DROOP*

N.C. Jaitly, M. Coleman, S. Eckhouse, and A. Ramrus
Maxwell Laboratories, Inc.
8888 Balboa Avenue
San Diego, California 92123
and
S.H. Gold, R.B. McCowan, and C.A. Sullivan
Beam Physics Branch
Plasma Physics Division
Naval Research Laboratory
Washington, D.C. 20375

Abstract

A compact 1 MV Long Pulse Generator, developed for high power microwave application of electron beam sources, is described. Such applications require voltage pulse flat-top with low ripple (≤ ± 1 percent) and low droop (≤ 2 percent). For the present application variable pulse widths of 0.1 to 10 μs into a fixed load (200 to 1 kΩ) up to 500 kV, and 0.1 to 1 μs for voltage above 500 kV and up to 1 MV were required. This pulse generator is presently in operation in the new Long Pulse Accelerator Facility at the Naval Research Laboratory, Plasma Physics Division.

Long Pulse Generator Description

The compact Long Pulse Generator, located in an oil-filled enclosure (6.5 ft wide x 6.5 ft deep x 10.5 ft long), is a turnkey system with the following major components. The relevant demonstrated performance specifications for this generator are listed in Table 1.

Table 1
Long Pulse Generator Specifications

Output voltage range	-250 kV to -1 MV
Load impedance range	200 Ω to 1 kΩ
Pulse width for voltage <600 kV	100 ns to 10 μs
Pulse width for voltage >600 kV	100 ns to 2 μs
Charging time for 1 MV pulse	~50 s
Maximum firing rate	15 shots/hr
Pulse to pulse reproducibility	< ±1%
Pulse rise time (10 to 90%)	<65 ns
Ripple 150 ns into the pulse	< ±1%
Voltage overshoot (1 kΩ load)	<10%
Droop for 1 kΩ load, 1 μs interval	2%
Droop for 200 Ω load, 10 μs interval	48%
Pulse-to-pulse jitter at 1 MV output	<5 ns

Marx Generator System

A 12-stage Maxwell standard Marx generator, with each stage consists of two parallel connected 0.4 μF, 100 kV capacitors (Maxwell Type-S), is used in the Long Pulse Generator. Fig. 1 shows the top view of the Marx generator. To increase the reliability of the system a nominal charge voltage of 90 kV per stage (rated at 100 kV) is used to deliver the 1 MV peak output pulse. The stored energy in the Marx erected capacitance of 66.7 nF at full output voltage is ~39 kJ. The Marx uses Maxwell standard gas plasma switches. The switches are mid-plane triggered and use UV irradiation in order to meet the low jitter requirement. Triggering of the switches in the first two Marx stages is initiated by a 100 kV precision Maxwell trigger generator. Both triggered switches have a closure jitter of <2 ns. The jitter associated with erection of the remaining Marx stages is minimized by resistively coupling the trigger pulse to the remaining switches in the Marx with two resistor chains. Each resistor in the chain connects the mid-planes of alternate stage switches and, in addition to coupling the trigger pulse to higher stage switches, also serves to bias the switch mid-planes to half the charge voltage.

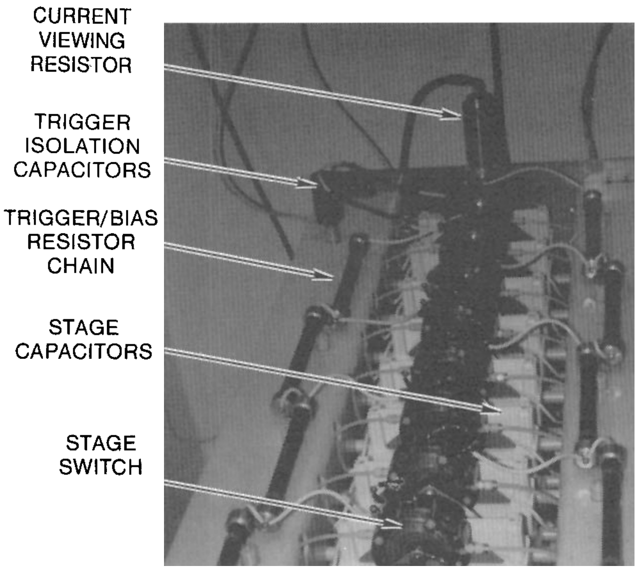

Fig. 1. Marx generator looking into the enclosure from the top.

High Voltage Charging Supply

A constant current (20 mA) charging supply, with digital voltage set-point, charges the Marx to 90 kV in ~50 seconds. To meet the pulse-to-pulse voltage amplitude specification of ±1 percent with the Long Pulse Generator fired anywhere in a time window of 15 seconds after charge completion a unique method is used. The power supply is designed to continuously regulate the Marx stage charge voltage to < ± 1 percent of the preselected voltage level until the triggering of the Long Pulse Generator. After triggering the Marx the power supply turns off via a trip circuit incorporated in the power supply. Measures were taken to protect the electronics in the power supply controller from the severe EMI environment present around the Generator when it is triggered. A timing circuit is also incorporated in the power supply controller so as to automatically dump the stored energy in the Marx if the trigger command to the Generator fails to arrive within 15 seconds after the completion of charge. Charge completion to the selected level is visually indicated on the controller. This helps in providing precise control of the output voltage amplitude from shot to shot.

*NRL Contract No. N00014-89-C-2133. Work at NRL supported by the Office of Naval Research.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
JUN 1991	**N/A**	**-**

4. TITLE AND SUBTITLE
1 MV Long Pulse Generator With Low Ripple And Low Droop

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Maxwell Laboratories, Inc. 8888 Balboa Avenue San Diego, California 92123

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. Held in San Francisco, CA on 16-21 June 2013. U.S. Government or Federal Purpose Rights License

14. ABSTRACT
A compact 1 MV Long Pulse Generator, developed for high power microwave application of electron beam sources, is described. Such applications require voltage pulse flat-top with low ripple (~ Â± 1 percent) and low droop (~ 2 percent). For the present application variable pulse widths of 0.1 to 10 J.lS into a fixed load (200 to 1 kQ) up to 500 kV, and 0.1 to 1 J.lS for voltage above 500 kV and up to 1 MV were required. This pulse generator is presently in operation in the new Long Pulse Accelerator Facility at the Naval Research Laboratory, Plasma Physics Division.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**SAR**	**5**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

1 MV Diverter Switch

The Long Pulse Generator can be triggered either manually from the control console or via a 10 V pulse provided externally to the console. The output pulse width is varied via a diverter switch located at the output of the Marx. A Maxwell time delay generator unit is used to provide 500 V trigger pulses. The first pulse appearing in sync with the trigger command (either manual or external) is the Marx trigger pulse. The second pulse with appropriate time delay, as determined by the output pulse width required, triggers a 100 kV precision trigger generator (identical to that used for the Marx) which fires the diverter switch to clip the output pulse. A third pulse delayed with respect to the diverter trigger pulse turns the charging supply off.

The diverter switch used here is a trigatron type switch as shown in Fig. 2. Use of SF_6 as an insulating gas provided a very compact switch which is triggered easily. This SF_6 insulated trigatron switch consists of a graded stacked insulator-ring outer envelope. The envelope comprises 10 acrylic insulator rings, ~0.9 in. thick, 9 in. OD, and a wall thickness of 0.75 in. Aluminum grading rings, with O-ring seals, are used to grade the voltage and seal the envelope. A total of 12 nylon tie rods, 0.75 in. in diameter, hold the switch together. The switch is strong enough to be pressurized to 100 psig. The overall switch envelope dimensions are 12.5 in. in diameter and 12 in. long.

The triggering of this switch is initiated by a mallory-tipped trigger pin located within the 0.25 in. diameter hole in the ground electrode. Both the ground and the high voltage brass hemispherical electrodes (~2 in. radius) have elkonite tips. The electrodes are separated by ~1.3 in.

Marx Output Resistor

To prevent voltage reversals in the Marx capacitors when the diverter switch closes and to absorb the energy stored in the Marx which reduces the wear associated with the diverter switch electrode, a compact high energy resistor is used. This resistor is located in series with the Marx output and prior to the diverter switch high voltage electrode connection. A unique, Maxwell designed, stainless steel element resistor with a rating of 10 Ω, 90 kJ is used. The resistance value chosen critically damps the Marx circuit eliminating voltage reversals in the capacitors. Further, this output resistor also gives the capability to operate the Long Pulse Generator directly into a short. The resistor element is constructed in a low inductance configuration resulting in a L/R time of <40 ns for the resistor. The resistor is provided with 4 corona rings along its 16 in. length for voltage grading. The resistor assembly is located in a 9 in. OD acrylic tube with an overall length of 18 in. The resistor is vacuum impregnated with transformer oil prior to assembly in the system.

Pulse Shaping Components

Voltage overshoot on fast rising pulse wavefronts and the resulting ripple on the pulse flat top are typical characteristics of ordinary Marx generators operating into high impedance loads. A snubber network system is used at the output of the Marx to control the magnitude of the output voltage overshoot and ripple. Two R-C type snubbers are located on either side and extend along the length of the Marx. Fig. 3 shows one of the R-C snubbers. Each of the snubbers consists of a 30 in. long, 1.5 in. OD ammonium chloride resistor in series with a single unit 1.4 MV capacitor. A 30 in. long, 2.5 in. OD aluminum pipe is used to connect the snubber to the Marx output corona ring. The snubbers are located approximately 12 in. above the bottom of the grounded Marx enclosure. The output pulse shape is optimized by appropriate choice of resistance and capacitance in each snubber. The snubber component values used for the present application are 140 Ω and 1.4 nF, respectively.

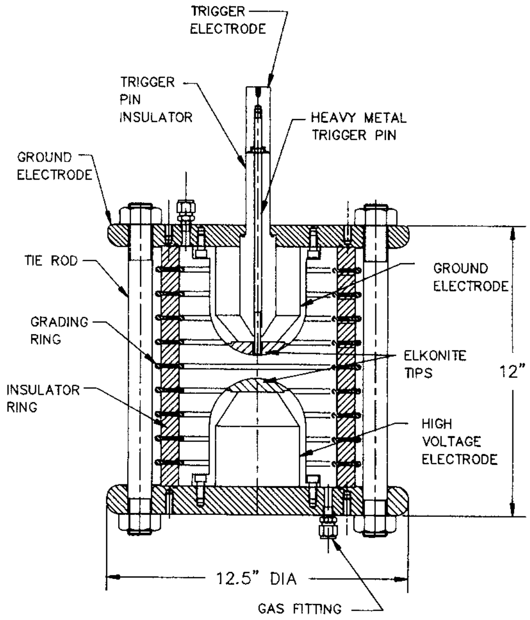

Fig. 2. SF_6 insulated, trigatron-type, 1 MV diverter switch.

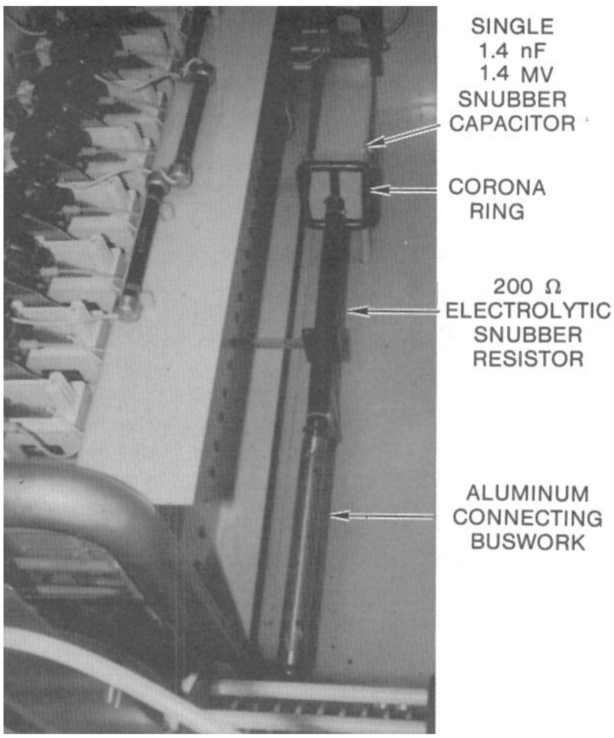

Fig. 3. Location of snubber no. 1 within the enclosure.

Careful design and computer analysis of the behavior of the Marx system and auxiliary components were undertaken to select the components used in the final design. The Marx charging and trigger coupling resistors constitute a shunt resistance across the Marx. By

keeping the charge and trigger resistors per stage at 10 and 11 kΩ, respectively, the effective shunt resistance to ground was kept at >30 kΩ. Hence the long time decay of the Marx is entirely governed by the value of the load (200 Ω to 1 kΩ) into which the Marx erects. The droop requirements for the load resistance in the range of 200 Ω to 1 kΩ dictated the required Marx capacitance of 0.8 μF per stage.

High Voltage Diode Section

The Marx output is connected to an electron beam diode section. This consists of a compact 1 MV, oil-vacuum graded, stacked-ring type feedthrough located within the Marx oil enclosure, and a stainless steel vacuum drift chamber located on the outside of the Marx enclosure, as shown in Fig. 4. The drift tube is 30 in. long with an outer diameter of 20 in. Located on the center axis of the diode is a 4 in. diameter cathode stalk which connects the Generator output to NRL load at the end of the drift tube. The cathode stalk centerline axis is located 3 ft above the bottom of the Marx tank enclosure. The drift tube is provided with a 6 in. pumping port to rapidly evacuate the chamber via an oil-diffusion pump down to 10^{-6} Torr.

The stacked-ring envelope of the feedthrough is made up of 8 machined acrylic rings, each 1.45 in. long axially, and an outer diameter of 24 in. The inner surface (vacuum side) of the acrylic ring has a 45 degree surface profile with respect to the diode axis while the outer edge (oil side) makes a 90 degree contact with the grading rings as shown in Fig. 4. The width at the base of the conical frustrum where the acrylic ring makes a 45 degree contact with the cathode end side of the grading ring is 2.5 in. wide. The acrylic rings are interspersed with aluminum grading rings having a

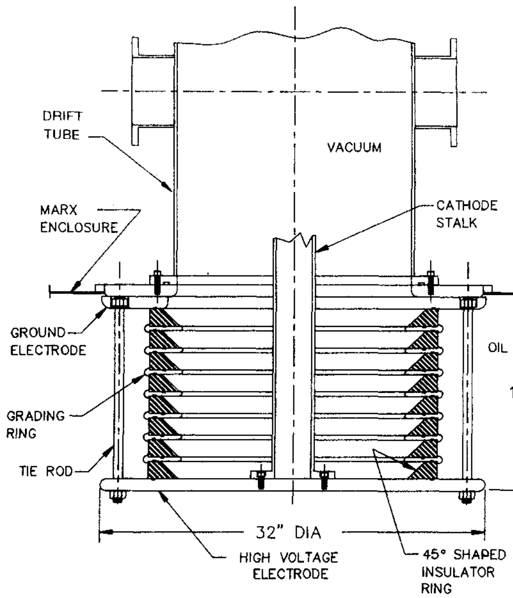

Fig. 4. High voltage diode.

0.25 in. radius of curvature on the edges. No recessing of the aluminum grading rings is done to relieve the stress at the apex end of the acrylic ring conical frustrum surface. The rings are in butt-type contact with the grading rings, and extreme care is taken to ensure all contact edges are sharp with no nicks or dings, and the surface finish in contact with the aluminum grading rings is better than a 32 finish. This oil-vacuum interface is held together between a grounded flange bolted to the enclosure output flange and a 1 in. thick aluminum high voltage electrode, with a well radiused edge, by 16 tie rods made from 0.75 in. diameter nylon material. The high voltage electrode end is connected to the Marx output (negative) via the 10 Ω output coupling resistor.

Design of the vacuum-insulator interface was based on the well known relationship $Ft^{1/6}A^{1/10} = K$ formulated by J.C. Martin. Here F is the (50 percent probability) surface flashover field in kV/cm, A is the insulator surface area in cm^2, and t is the effective time in microseconds for which the insulator is stressed to greater than 89 percent of the peak voltage. This empirical equation has been found to be valid both for 45 degree insulator profile and diaphragm-type insulators and is widely used for diode designs for short duration pulsers typically in the range of $10 < t < 200$ ns. Not much is known about the use of this equation for design of interfaces above t = 1 μs. The commonly used value of the constant K is in the range of 170 to 175 for the effective times mentioned above.

No long pulse design data for the region of interest (t = 10 μs) was available in a useable form to assist in the design. The above empirical equation was, therefore, used allowing comfortable margins in the design parameters. The outer diameter of the insulator-ring stack and the drift chamber in our design is fixed by the criterion that the electric field on the surface of the cathode stalk was kept at a reasonable value (~125 kV/cm). For the acrylic ring dimensions outlined above, the surface area of each ring was 830 cm^2. Thus for t = 2 μs, the breakdown stress (50 percent probability) from the equation was determined to be ~80 kV/cm. Hence, for a ring thickness of 1.45 in., the 50 percent probability flashover voltage was estimated at 294 kV. Taking half the value of this flashover voltage (~147 kV) as the allowable stress per ring, and designing the insulator-ring stack for a voltage of 1.2 MV, a total of 8 such rings were required.

Self-Break Oil Switch

To protect the oil-vacuum high voltage feedthrough from accidental overstress at 1 MV (maximum pulse duration limited to 2 μs), a self-break oil switch in the form of a sphere-plane gap is used. This switch is required in the event that the diverter fails to fire. A 50 Ω, 75 kJ stainless steel element resistor is connected in series with this gap as shown in Fig. 5. This gap is connected to the high voltage flange of the oil-vacuum feedthrough. The gap spacing has been adjusted such that no spurious gap closures occur for the 2 μs pulses at 1 MV. Should the pulse duration exceed 2 μs, the oil-switch is set to close in order to prevent overstress of the oil-vacuum feedthrough. The energy stored in the Marx will be absorbed in the 50 Ω resistor present in series with this oil gap.

Diagnostics

A low inductance coaxial current shunt (2.5 mΩ, 3 kJ) is used as a current viewing resistor to monitor the total current delivered by the Marx. It is located on the ground side of the first stage in the Marx as shown in Fig. 1. The shunt has a rise time of 45 ns and a bandpass of 8 MHz.

An ammonium chloride liquid voltage monitor is used to measure the voltage appearing at the high voltage electrode of the oil-vacuum feedthrough. This monitor also serves as the resistive load into which the Marx erects during initial tests. This Marx voltage monitor/load resistor has an active length of 62 in. with a diameter of 1.5 in. It is connected between the high voltage electrode of the diverter switch and the Marx enclosure wall. The voltage monitor/load is partly visible in Fig. 5.

Long Pulse Generator Performance

Tests were conducted using negative output pulses. The load during the tests assumed fixed values of either 200 Ω or 1 kΩ. The pulse-to-pulse flat-top amplitude reproducibility of <1 percent has

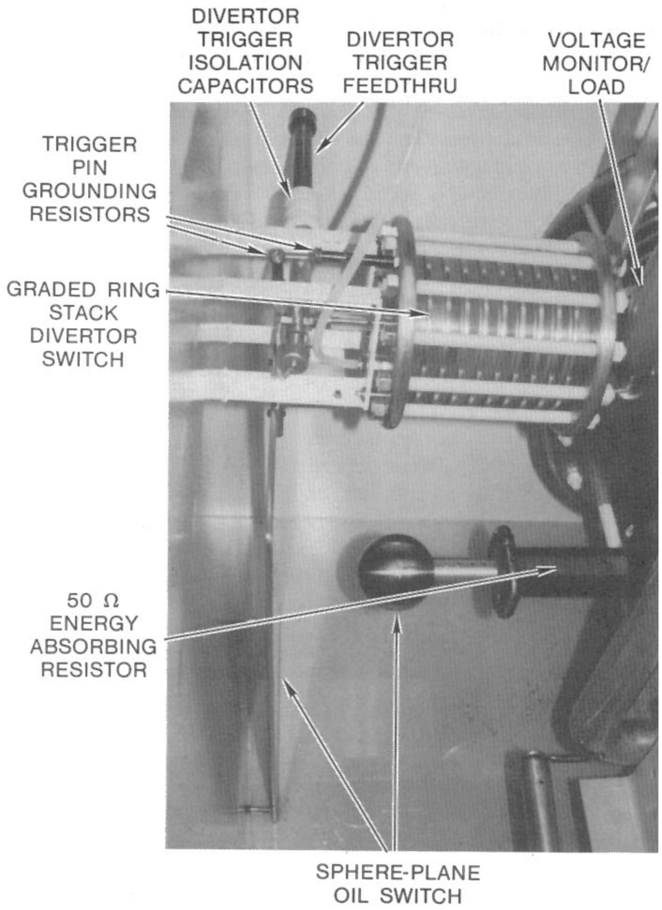

Fig. 5. Location of diverter switch and oil switch.

been achieved. The pulse rise time (10 to 90 percent) into 200 Ω load is <65 ns; the rise time into 1 kΩ being faster. The output pulse-to-pulse jitter has a standard deviation of <10 ns at the low end of the Marx output voltage. This jitter at 1 MV output is <5 ns.

Fig. 6 shows the output voltage waveshapes (recorded on Tektronix 2430) with and without the snubber network for 1 kΩ load. It is evident that the voltage overshoot and oscillations are significantly reduced by the snubber network. The bottom trace represents the Marx current. A large increase in current is evident when the diverter switch fires to clip the voltage pulse. Both traces are inverted. Fig. 7 shows the output waveshape at 1 MV (recorded on Tektronix DSA602 during acceptance tests at NRL) after

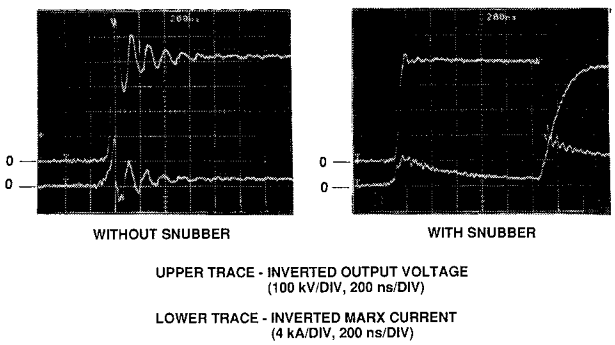

Fig. 6. Waveshape for 1 kΩ load with and without snubber.

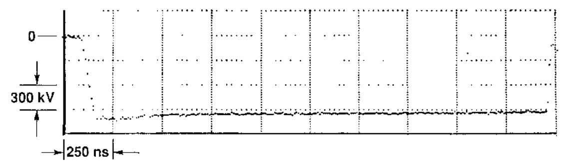

Fig. 7. Waveshape for 1 kΩ load with an optimized snubber.

optimizing the snubber network. A pulse width >2 μs is evident along with negligible overshoot. The diverter switch SF_6 pressure was 65 psig nominal for 1 MV operation. Expanding the flat-top portion of the pulse by offsetting the baseline on the scope, the measured ripple 150 ns into the pulse flat-top was found to be <±1 percent and the droop over the first 1 μs into the pulse was about 2 percent for the 1 kΩ load case. Ripple for the 200 Ω load was significantly lower.

The diverter is readily triggered 10 μs into the pulse. A typical waveform is shown in Fig. 8 for a 1 kΩ load case. The voltage withstand capability of the ring-stack envelopes used in the oil-vacuum interface and the diverter switch for exponentially decaying waveshape was extensively tested at full voltage of the Long Pulse Generator into the 200 Ω load. In these tests the oil switch was disconnected and the trigger pulse to the diverter switch was removed, thus forcing the ring-stack envelopes of the oil-vacuum feedthrough and the diverter switch to an R-C decay type 1 MV pulse. Several shots were fired with no failure. Fig. 9 shows the undiverted voltage pulse shape used during these voltage withstand tests. Tests with 1 kΩ load using undiverted pulses were limited to ~600 kV. No failures were encountered during these tests.

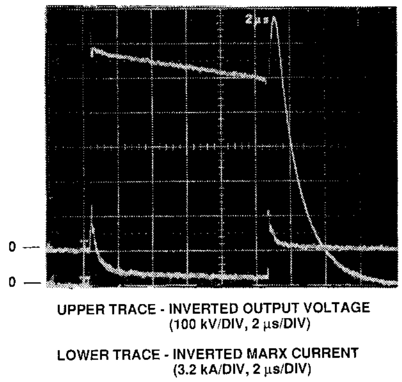

Fig. 8. Waveshape for 1 kΩ load with diverter clipping the pulse at 10 μs.

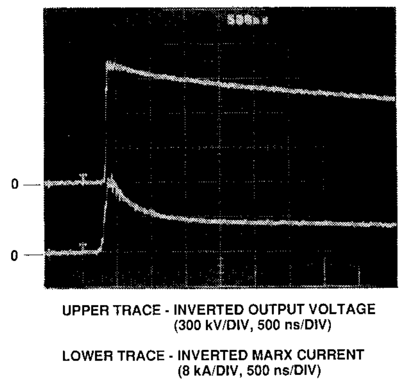

Fig. 9. Undiverted voltage pulse for 200 Ω load at full voltage.

Conclusions

A very compact, turnkey, Long Pulse Generator system capable of delivering high quality pulses has been successfully designed, fabricated, tested, and delivered. During the development and testing of this generator, important data pertaining to long pulse (several microseconds) behavior of oil-vacuum interface, oil-gas interface, and bulk transformer oil has been obtained. A unique method to generate high quality pulses by using a state-of-the-art snubber circuit has been demonstrated. A very compact SF_6 insulated trigatron diverter switch and an oil-vacuum high voltage feedthrough capable of 1 MV operation has been developed.